Novel Whispering-Gallery Resonators for Oscillators, Modulation and Sensing

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Contributions and collaborations acknowledged

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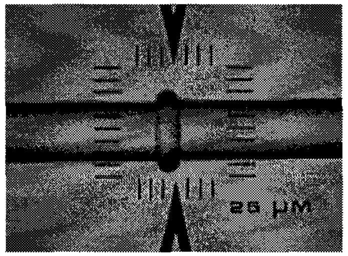
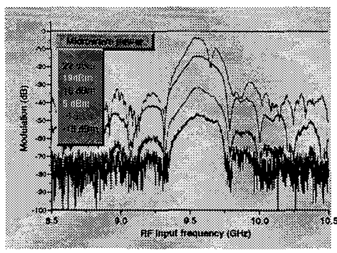
Anthony Levi	*(USC)*
Michael Gorodetsky	*(Moscow State)*

1. Microtorus: a novel high-finesse microcavity



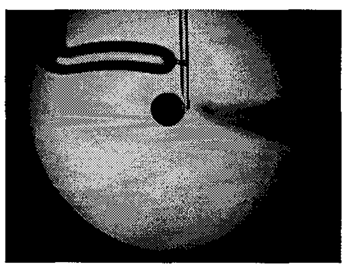
The highly oblate spheroidal dielectric microcavity combines very high Q-factor, typical of microspheres, with vastly reduced number of excited whispering-gallery (WG) modes

2. Microwave modulation using whispering-gallery modes



Spherical cavity of lithium niobate serves as a core for low-controlling-power electrooptical modulator

3. WG microcavity as a sensor: detection of nanomole dopants in fluids



Very high intrinsic Q of immersed microspheres allows for detection of dilute absorptive species in the evanescent field

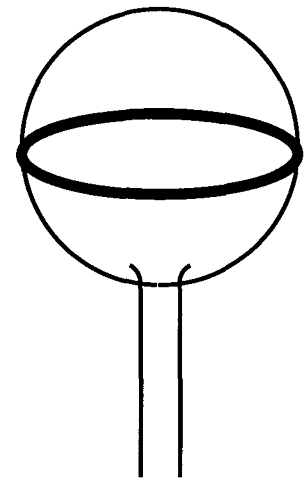
Microspheres have been here

low material loss (transparent material)

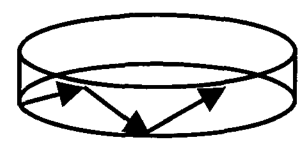
low bending loss (high-contrast boundary)

LOW SCATTERING LOSS (TIR always under grazing incidence) $\Theta \to \pi/2$; compare to disks/ rings:

$$\frac{I_R}{I_I} = e^{-\left(\frac{4\pi\sigma}{\lambda}\cos\Theta\right)^2}$$ (J.W.S.Rayleigh)



EVEN WITH MOLECULAR ROUGHNESS σ, ONLY CURVATURE CONFINEMENT ALLOWS **Q** LIMITED BY MATERIAL ATTENUATION:



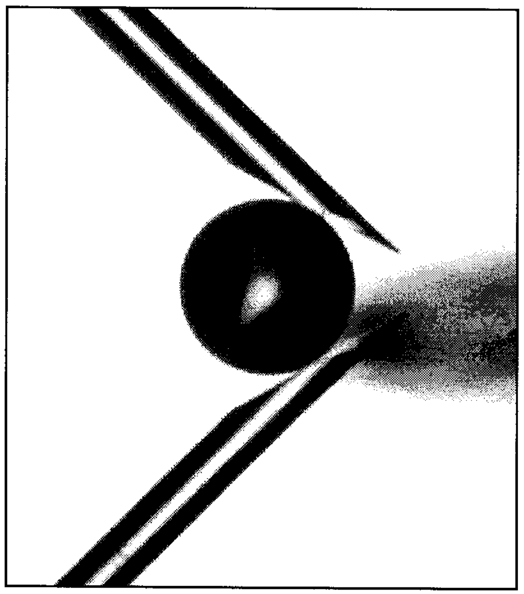
10^8 -10^{10} in spheres vs. 10^3 - 10^5 in microrings !!

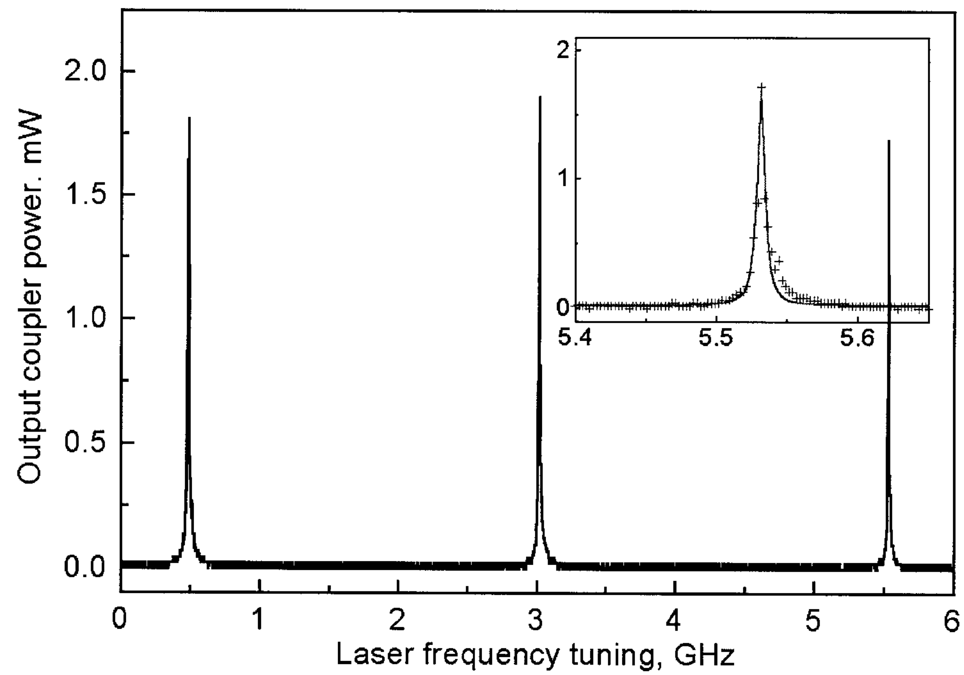
Drawback: “too many modes” compared to planar rings!

Spectrum of microspheres: Families of non-degenerate $TE(TM)_{lmq}$ modes.

"Small" FSR $\nu_{lmq} - \nu_{l,m-1,q} \sim \nu \dfrac{\varepsilon^2}{2l}$ - few GHz with typical ε^2 ~(1-3) $\times 10^{-2}$.

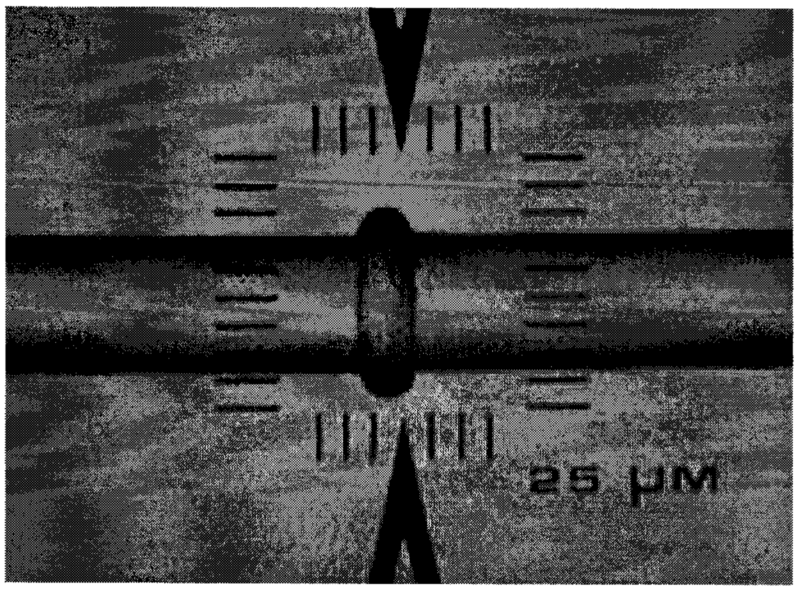
"Big" FSR $\nu_{lmq} - \nu_{l-1,mq} = \dfrac{c}{2\pi n a}(t_{lq} - t_{l-1,q}) \sim \nu / l$ - few hundred GHz (few nm)

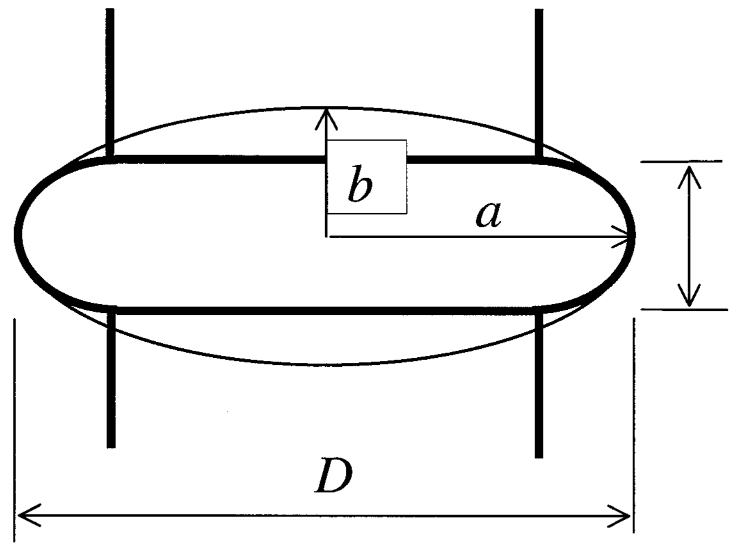




Input power 7.5…8.3mW; maximum transmission at resonance ~23.5% (fiber-to-fiber loss 6.3dB); $Q_{load} > 3 \times 10^7$ at 1550nm; sphere diameter 405μm. Unloaded $Q_o \approx 1.2 \times 10^8$ *(Opt.Lett. 24, 723 (1999))*

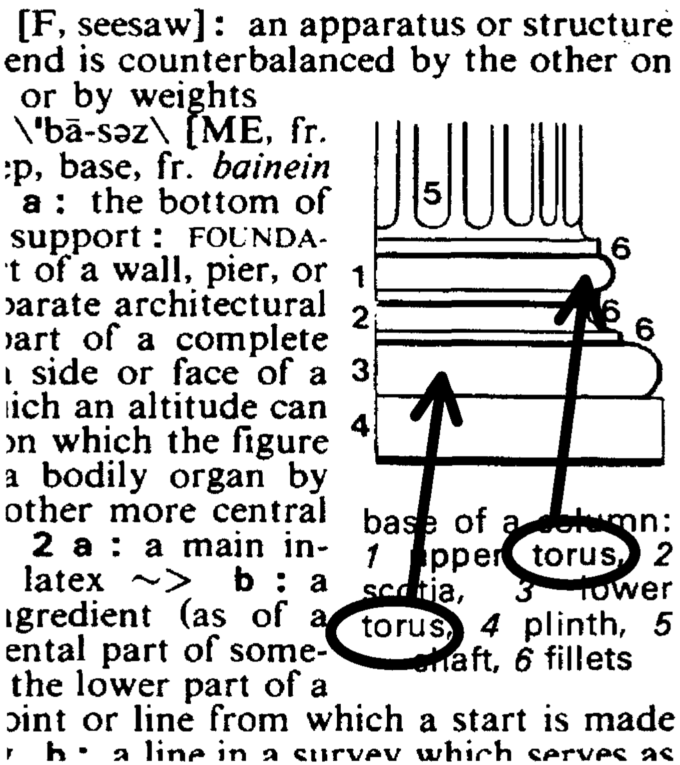
Novel geometry: a highly oblate spheroid, or microtorus





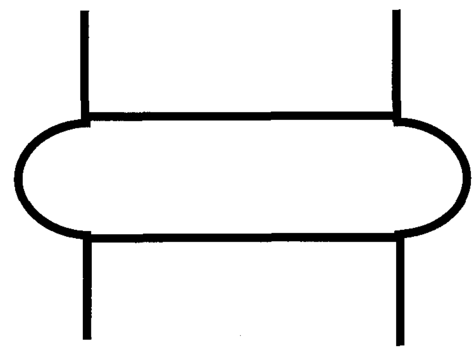
Near the symmetry plane (at the location of WG modes), toroidal surface of outer diameter D and cross-section diameter d coincides with that of the osculating oblate spheroid with large semiaxis $a = D / 2$ and small semiaxis $b = \frac{1}{2}\sqrt{Dd}$

Names



[F, seesaw] : an apparatus or structure
end is counterbalanced by the other on
or by weights
\'bā-səz\ [ME, fr.
:p, base, fr. *bainein*
a : the bottom of
support : FOUNDA-
t of a wall, pier, or
parate architectural
part of a complete
side or face of a
ich an altitude can
on which the figure
a bodily organ by
other more central
2 a : a main in-
latex ~> b : a
gredient (as of a
ental part of some-
the lower part of a
oint or line from which a start is made
b : a line in a survey which serves as

base of a column: *1* upper torus, *2* scotia, *3* lower torus, *4* plinth, *5* shaft, *6* fillets



(Webster's New College dictionary; *G & C Merriam Co. Springfiled, Mass., 1975, p.92)*

Calculation of the spectrum of the dielectric spheroid

is not a trivial problem, even numerically. In "quasiclassical" approximation with assumptions:

1) a WG mode is a closed circular beam supported by TIR, 2) optical field tunnels outside at the depth $1/k\sqrt{n^2-1}$, and 3) the tangential component of E (*TE*-mode), or normal of D (*TM*-mode) is continuous at the boundary. Eigenfrequencies of high-order WG modes ($l >> 1; l \approx m$) in dielectric sphere can be approximated via solutions of scalar wave equation with zero boundary conditions, because most of the energy is concentrated in one component of the field (E_θ for *TE*-mode and E_r for *TM*-mode).

Based on above considerations, let us estimate WG mode eigenfrequencies in oblate spheroids of large semiaxis a, small semiaxis b, and eccentricity $\varepsilon = \sqrt{1-b^2/a^2}$. Since WG modes are localized the "equatorial" plane, we shall approximate the radial distribution by *cylindrical* Bessel function $J_m(n\tilde{k}_{mq}r)$ with $n\tilde{k}_{mq}a = na\sqrt{k_{lmq}^2 - k_\perp^2} \approx T_{mq}$, where $J_m(T_{mq}) = 0$ and $k_\perp$ is the wavenumber for quasiclassical solution for angular spheroidal functions. For our purposes a rough approximation is enough: $k_\perp^2 \approx \dfrac{2(l-m)+1}{a^2\sqrt{1-\varepsilon^2}}m$;

more rigorous consideration can follow the approach given in [*I.V.Komarov, L.I.Ponomarev, S.Yu.Slavyanov, Spheroidal and Coulomb Spheroidal Functions, Moscow,Nauka (1976) (in Russian)*]. Taking into account that $T_{mq} \approx t_{lq} - (l - m + 1/2)$, we finally obtain the following approximation:

$$nk_{lmq}a - \frac{\chi}{\sqrt{n^2-1}} \approx t_{lq} + \frac{2(l-m)+1}{2}\left(\frac{1}{\sqrt{1-\varepsilon^2}} - 1\right)$$

t_{lq} -- q-th zero of the spherical Bessel function of the order l; $\chi = n$ for *TE*-mode, $\chi = 1/n$ for *TM*-mode.

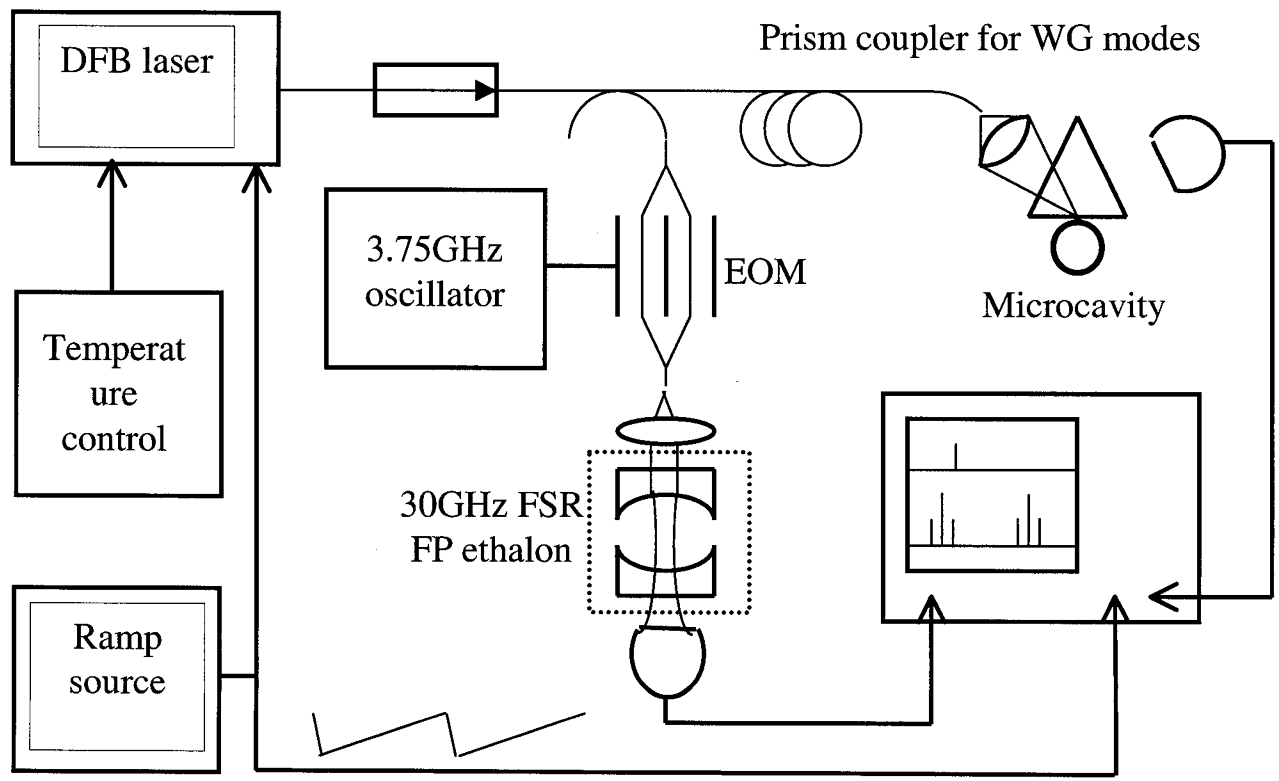
1. For small eccentricities the model gives identical prediction with perturbation theory *(H.M.Lai, P.T.Leung, K.Young, P.W.Barber, S.C.Hill, Phys. Rev. A 41, 5187-5198 (1990))*
2. Discrepancy with numerical calculations is <5% in prediction of "small" FSR and <0.1% of absolute frequencies, even with $\varepsilon^2 \sim 0.8$, even small $l = 100$

Schematic of the experimental setup

to obtain wide range (~900GHz, or 7.2nm) high-resolution spectra of WG modes in microcavity

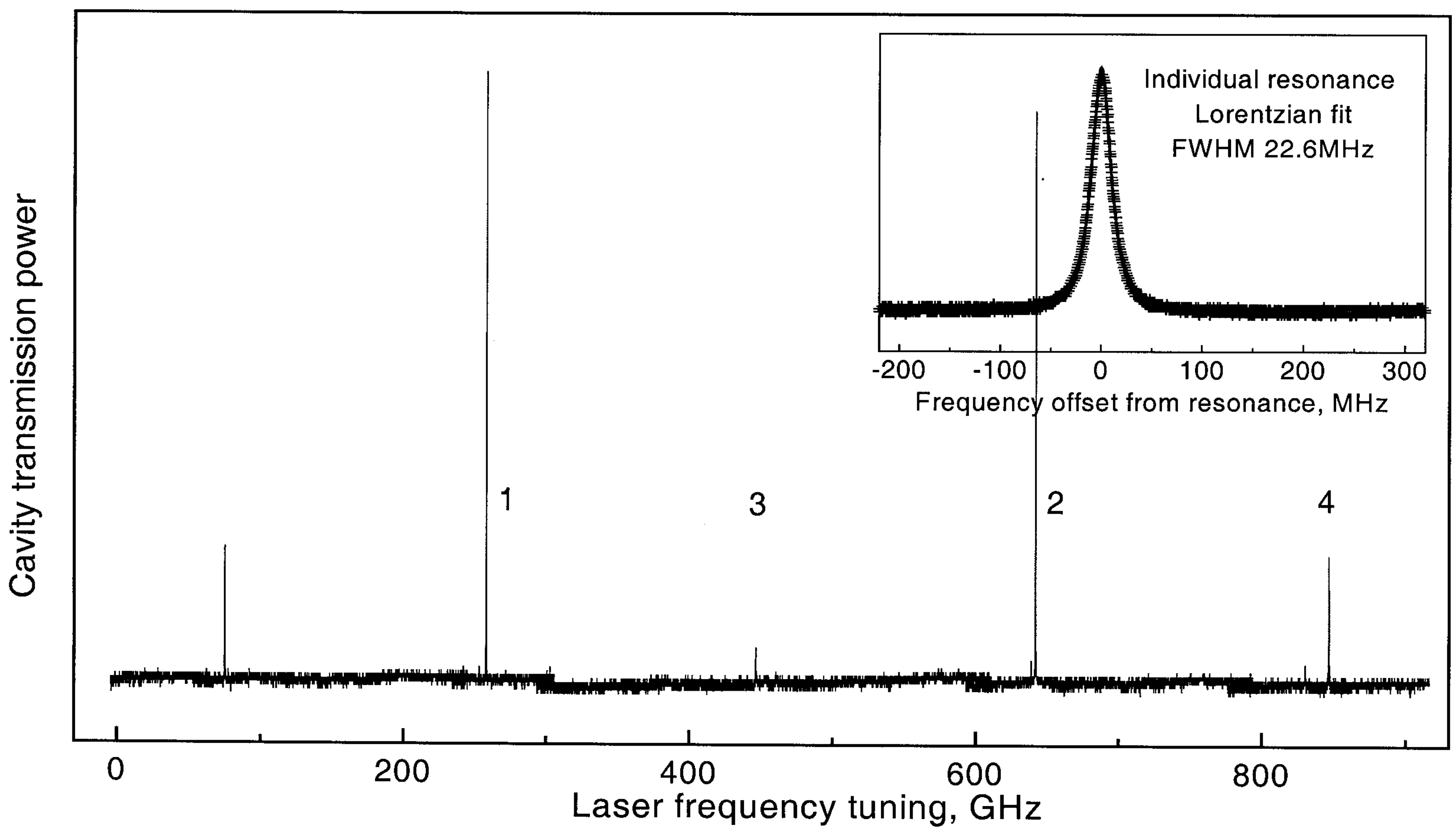
Fifteen 60GHz steps to cover 900GHz (between1545.1 and 1552.4nm)

80GHz sweep



Spectrum of *TE* whispering-gallery modes in spheroidal dielectric microcavity

$D = 2a = 165\mu m$; $d = 42\mu m$; $2b = 83\mu m$. Free spectral range (between largest peaks 1 and 2) 383.7GHz (3.06nm) near central wavelength 1550nm. Individual resonance bandwidth 23MHz (loaded $Q = 8.5\times10^6$). Finesse $F = 1.7\times10^4$



Main experimental result: "small" FSR gets large

Our parameters: $a = 82.5\mu m$, $b = 42.5\ \mu m$ ($\varepsilon = 0.86$), n = 1.453, λ ~1550nm, *TE*-modes $l \approx 473$

Estimate of "large" FSR (calculations)

$$\nu_{lmq} - \nu_{l-1,mq} = \frac{c}{2\pi na}(t_{lq} - t_{l-1,q}) = \frac{c}{2\pi na}(1 + 0.617 l^{-2/3} + O(l^{-5/3})) \approx 402 GHz$$

Estimate of "small" FSR

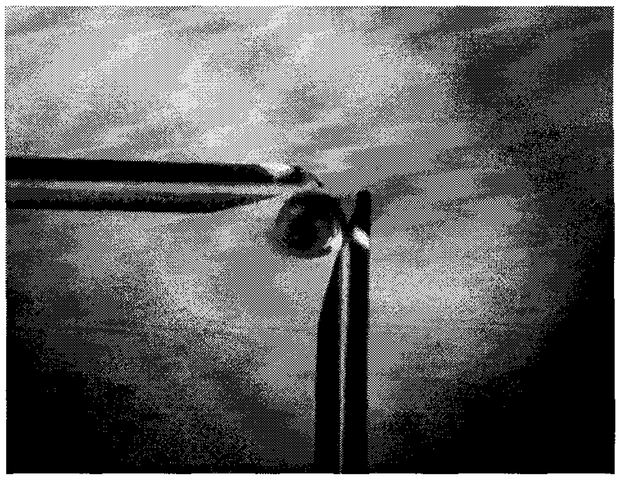
$$\nu_{lmq} - \nu_{l,m-1,q} = \frac{c}{2\pi na}\left(\frac{1}{\sqrt{1-\varepsilon^2}} - 1\right) \approx 382 GHz$$

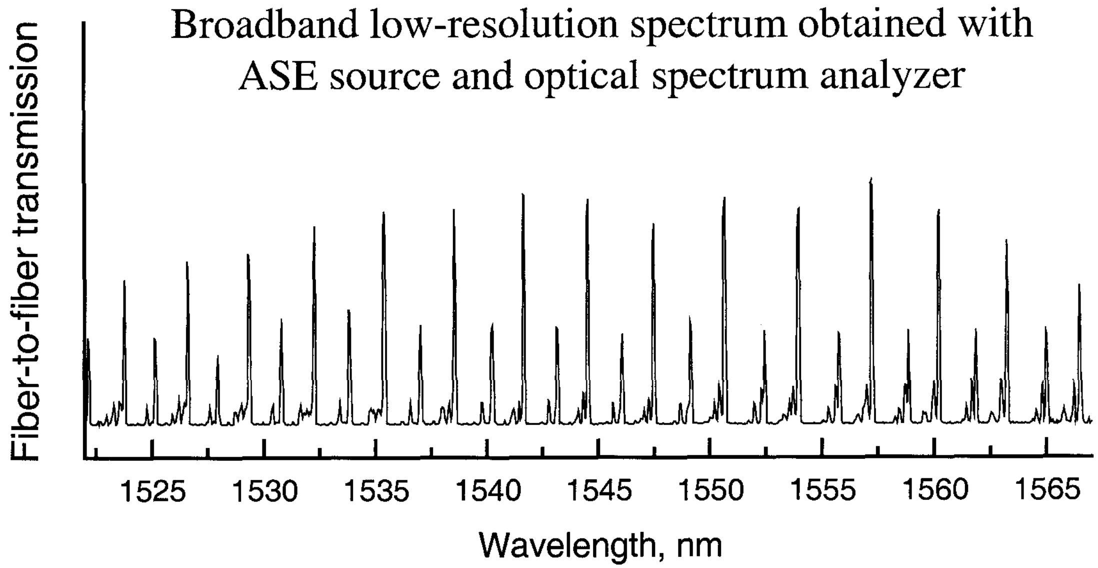
Experimental spectrum:	peaks 1-2	383.7±0.5 GHz
	peaks 3-4	400.3 ±0.5 GHz

Question yet to answer:

exact mechanism of coupling roll-off for different $\boldsymbol{l}$ *mode families*

Are there dispersion mechanisms to alter spectral character "in wide"?

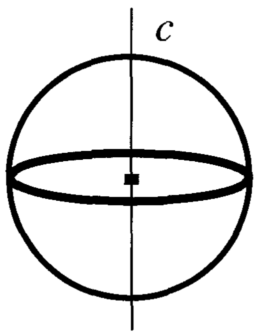




CONCLUSION

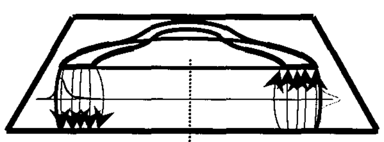
1. It seems indeed we can combine small size, ultra-high-Q with "nice" FP-like spectrum for true finesse 10^4 - 10^6 -- in microcavities as opposed to "super"mirror FPs
2. Complete "mode cleaning" can be expected with higher eccentricities; higher Qs -- with refinement of fabrication
3. Potential applications may be diverse

Electro-optic modulation with whispering-gallery modes



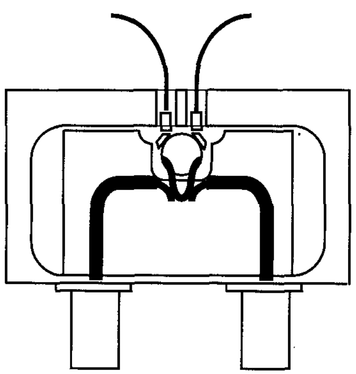
Optical whispering-gallery modes in lithium niobate sphere in the perpendicular plane to principal crystal axis.

Optical FSR is the operational microwave frequency



Equatorial layer is sliced out of the sphere and microwave cavity(ies) is (are) built around.

Variation of microwave field phase along the circumference is required to satisfy momentum conservation in 3 photon process by $\chi^{(2)}$

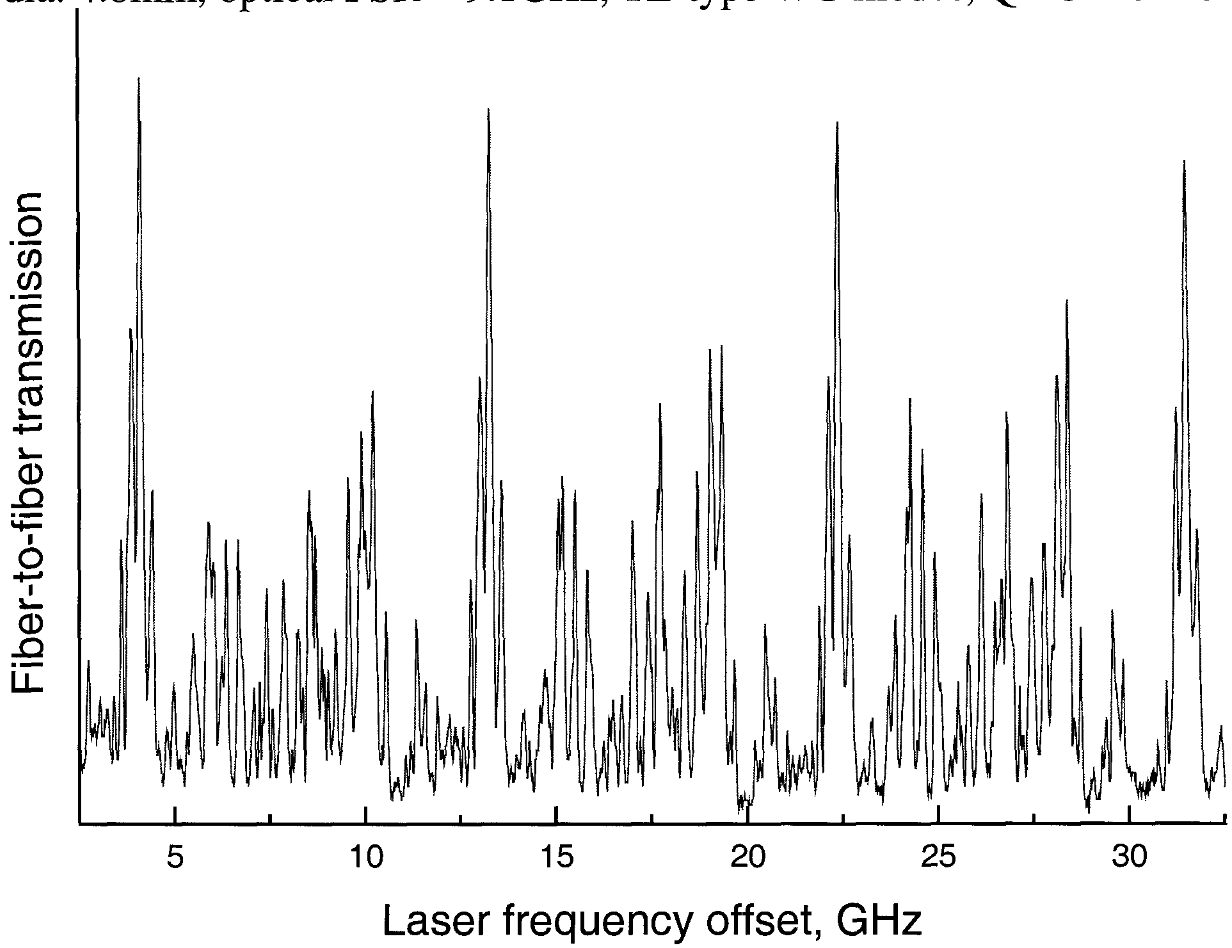


The setup is completed with microwave coupler(s), one or two optical coupling prisms, and fiber collimators

Typical optical spectrum obtained with single prism and two fiber collimators

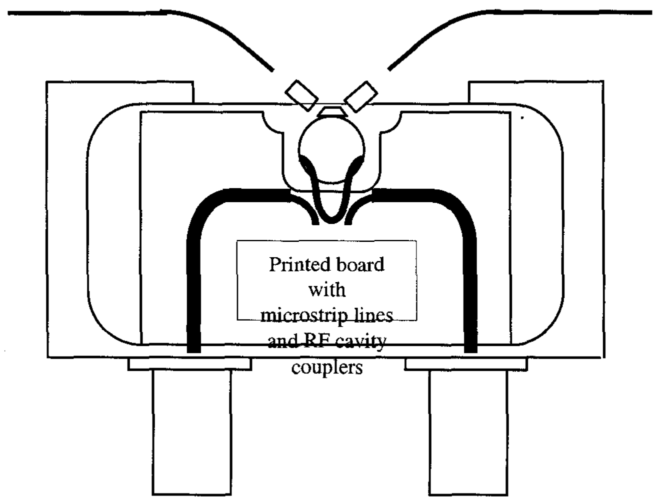
separate peak prominence highly dependent a)on launch angle vs crystal axis b)position of pick-up fiber.

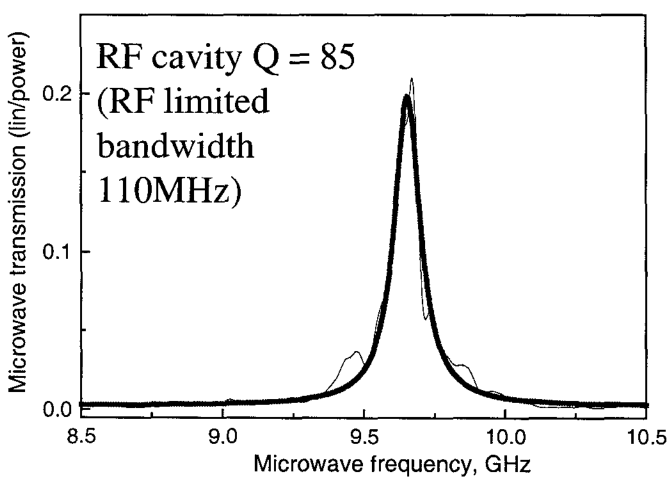
"Disk" dia. 4.8mm, optical FSR ~ 9.1GHz, TE-type WG modes, Q ~ 3×10^6 @ 1550nm



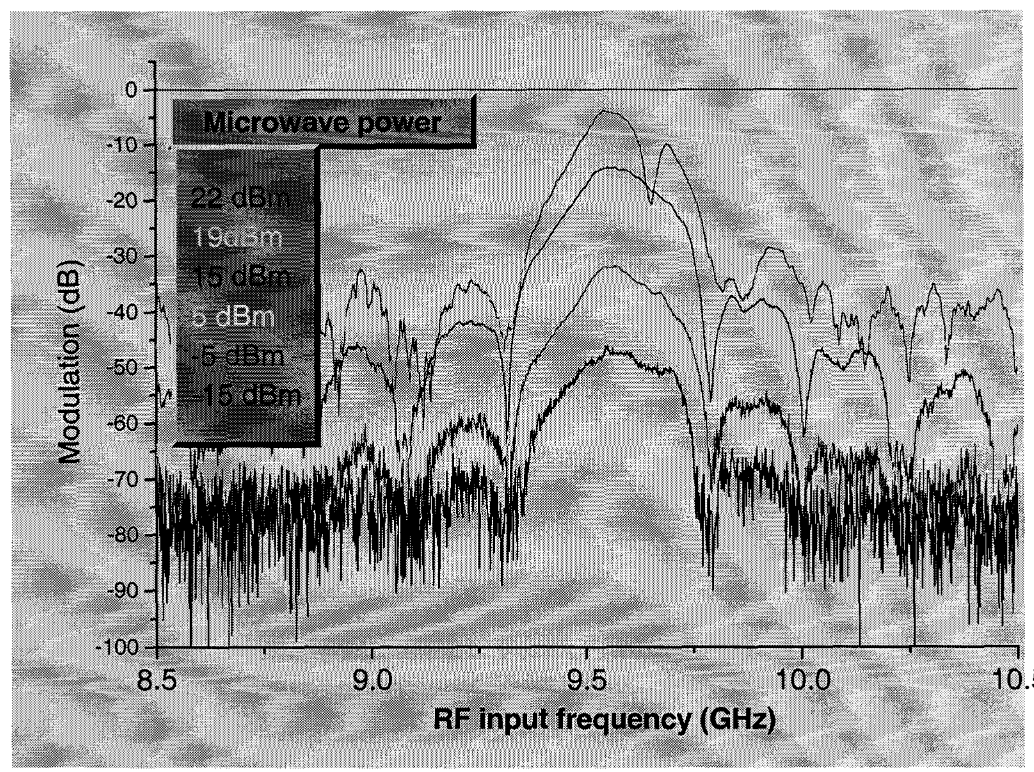
Variant 1: single "horseshue" MW cavity, "disk" with 4.6mm dia., 0.75mm height

Curved adaptation of a half-wave open-end microstrip-line resonator



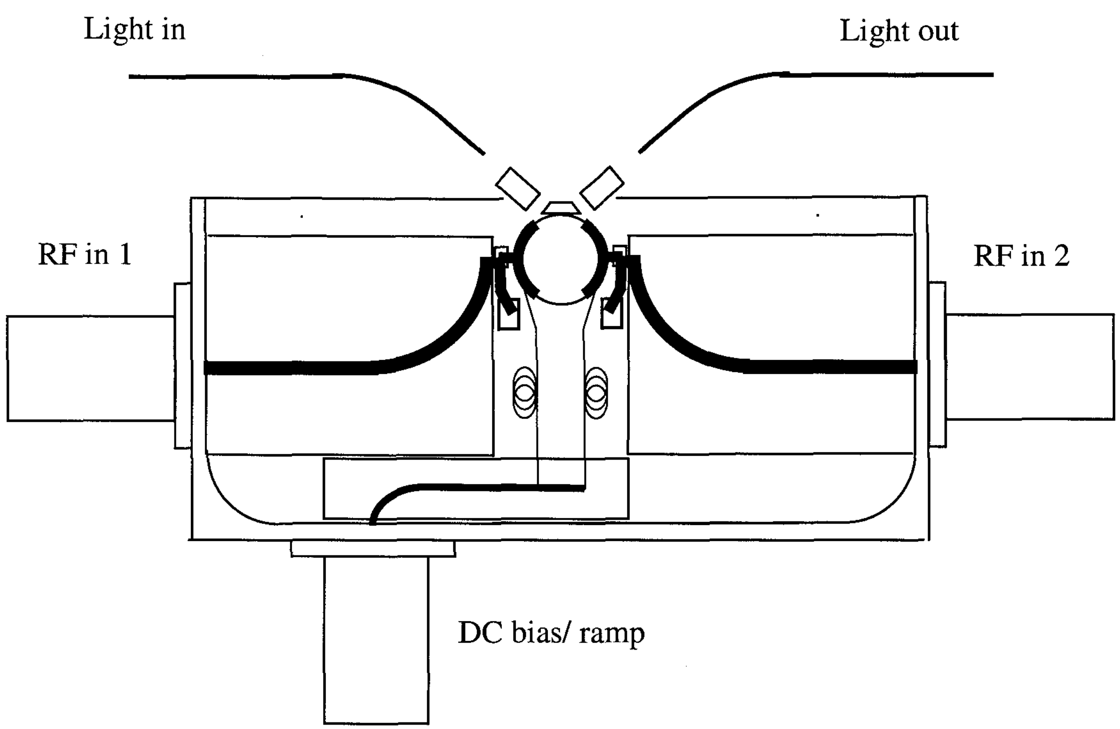


Frequency response of the modulator

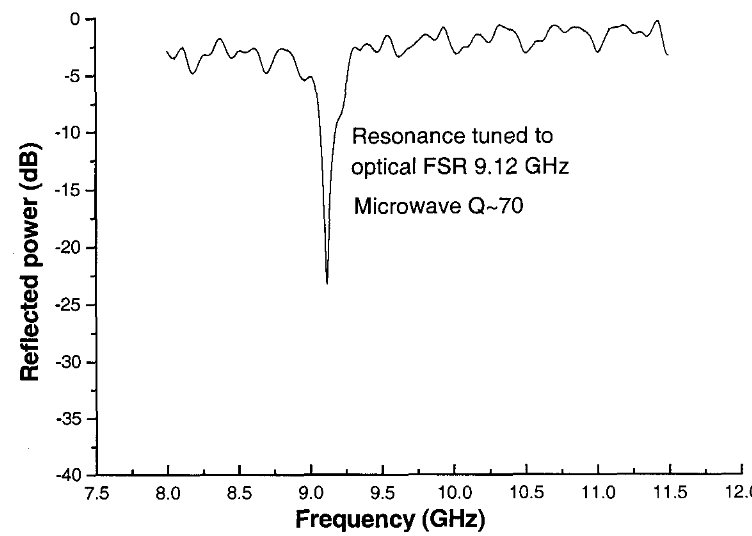


Variant 2 (two tunable MW cavities), "disk" with 4.85mm dia., 0.39mm height

Branched half-wave microstrip cavities tunable by quasi-lumped capacitor at idle end

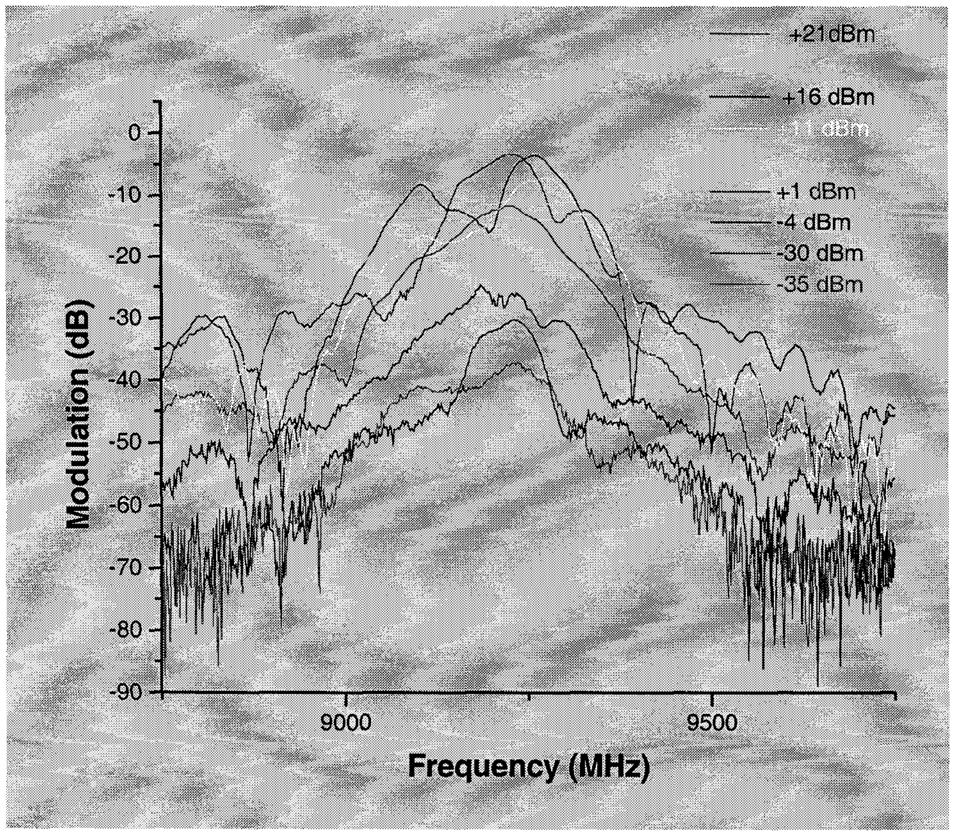


Microwave resonance at port 1



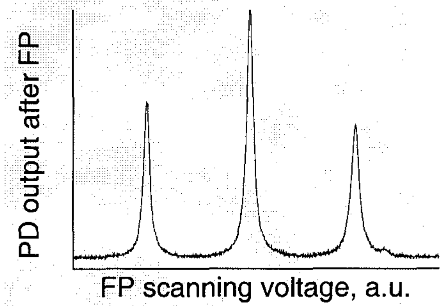
Variant 2, microwave modulation

Frequency response of the modulator (one port driven so far)



Optical Spectrum of Modulated Signal

9.2GHz sidebands maximized by adjusting output coupler

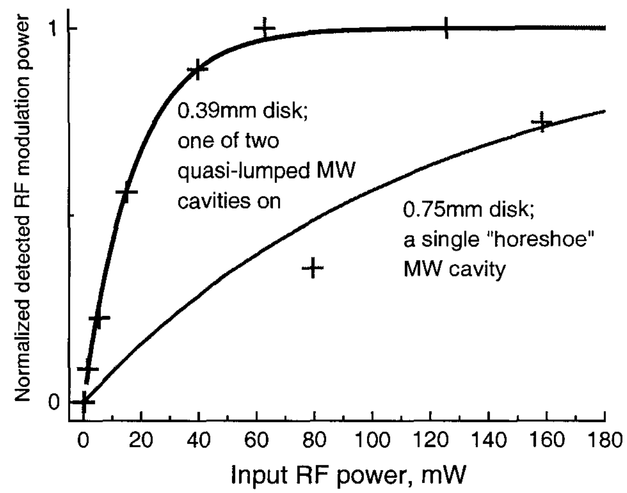


RF power to drive the modulator:

~40mW with just one RF cavity

Compare to ~1W in Mach-Zender

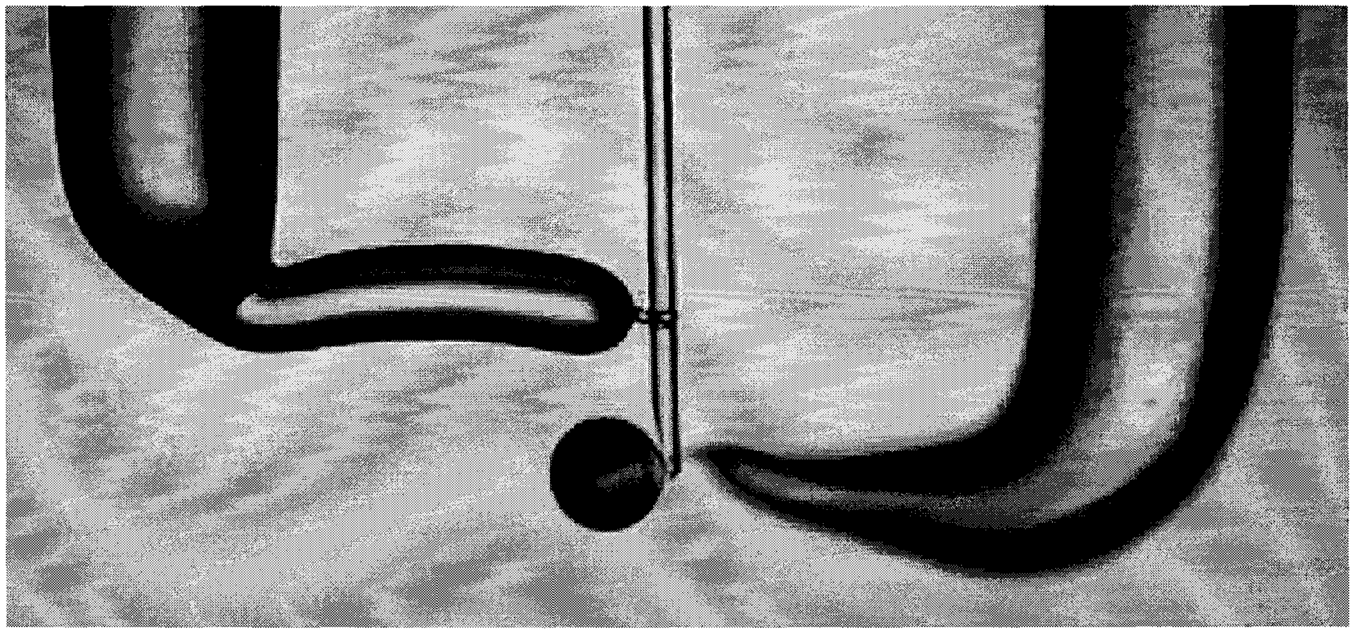
Lots of room to go



Electro-optic modulation with whispering-gallery modes (conclusion)

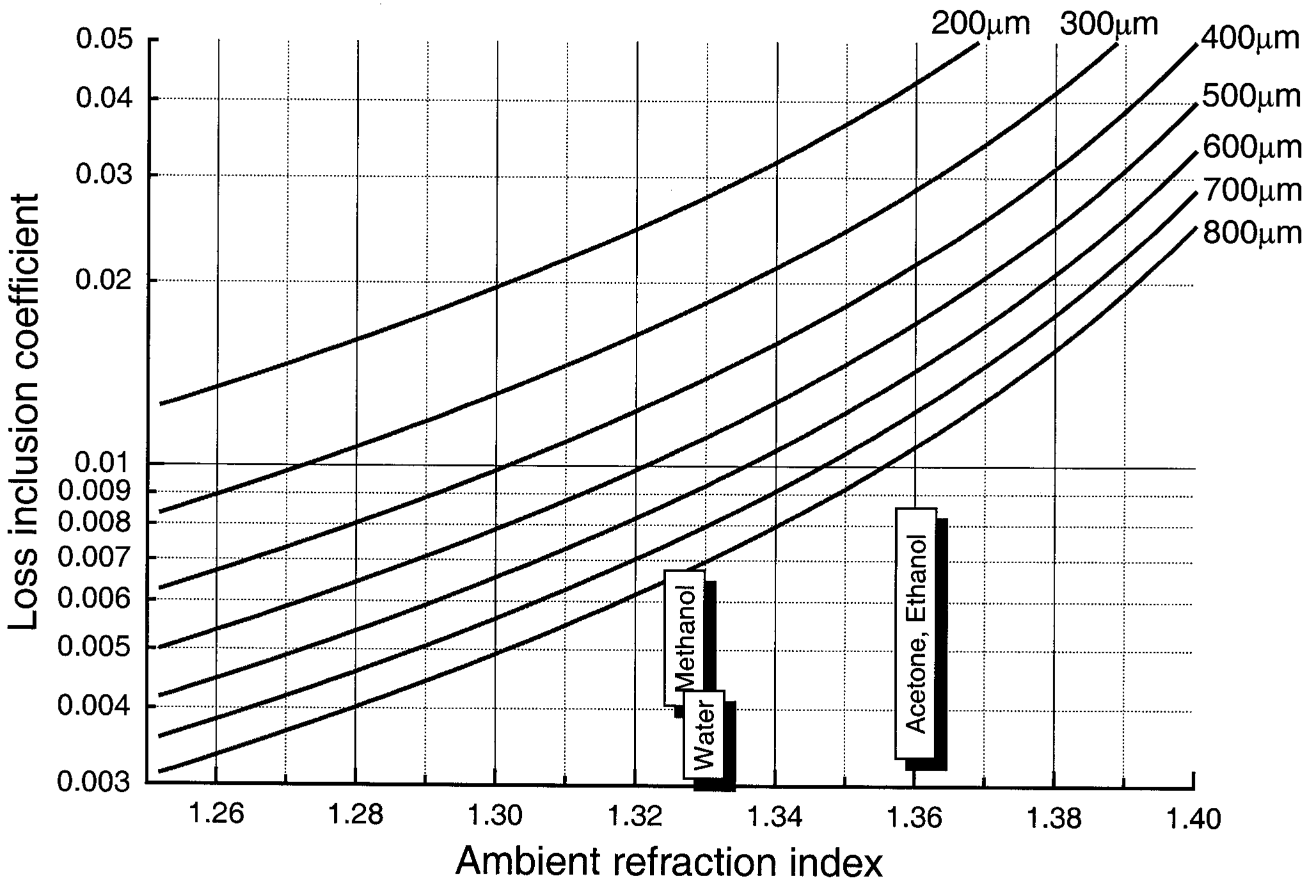
- Optical losses in lithium niobate allow for high-Q (0.3-1)$\times 10^7$ WG modes. High finesse translates into potential of strong reduction of controlling electrical power compared to zero-order interferometers such as MZ
- RF driving power can be further reduced by matching microwave cavity that can be as high-Q as 10^3 (limited by dielectric loss)
- Limited band, non-power-hungry modulators (1mW and less is feasible) may be useful for mm-wave applications such as low-rate data, fiber radio & picocellular com, as well as in novel optoelectronic oscillators

WG microcavity as a sensor: detection of nanomole dopants in fluids



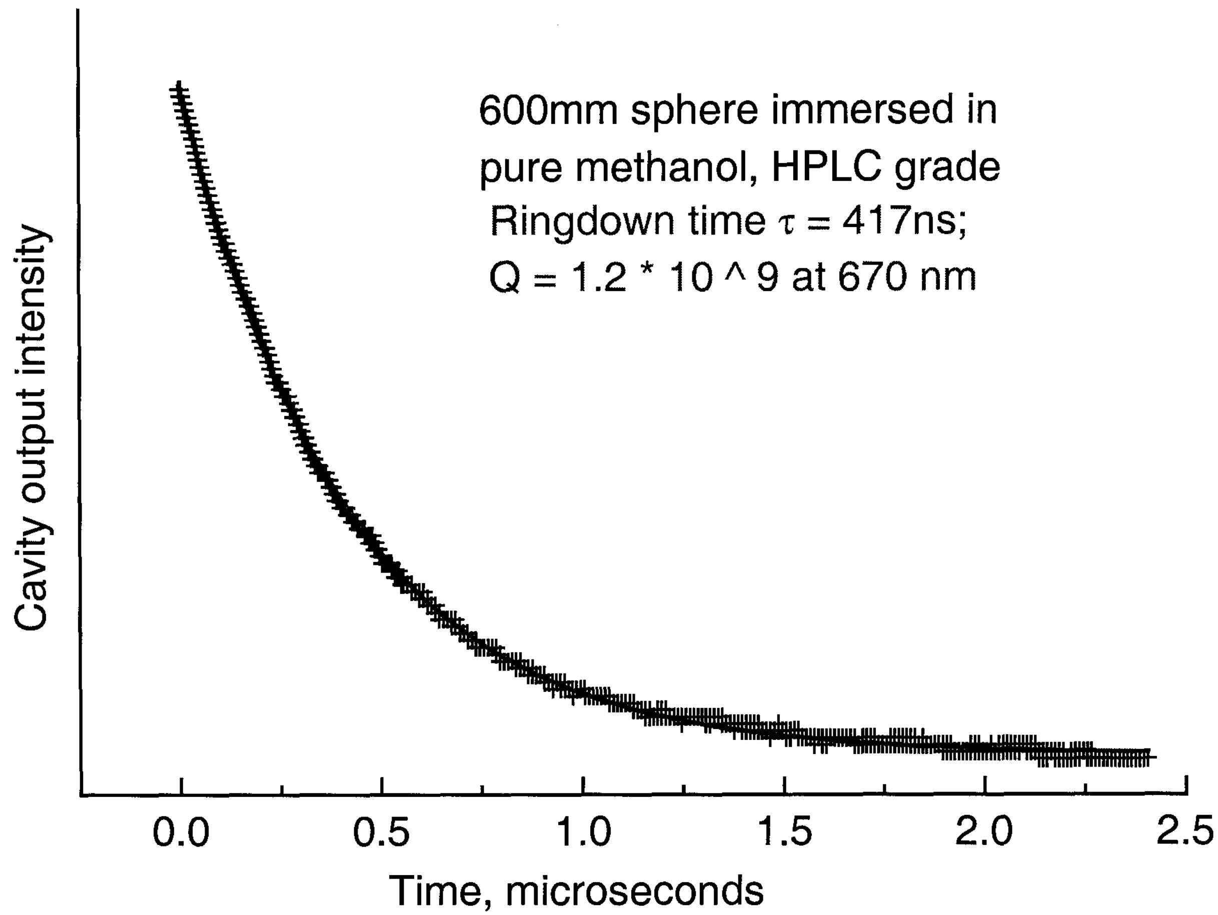
Evanescent wave makes the Q-factor of WG modes a function of optical loss in the ambient. Alternatively, the resonator becomes a miniature replacement of intracavity absorption cell

Loss inclusion coefficient; immersion of silica spheres of different diameters; wavelength 670nm

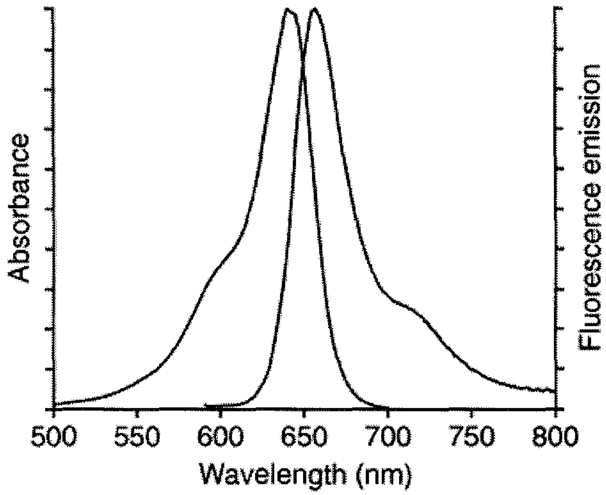


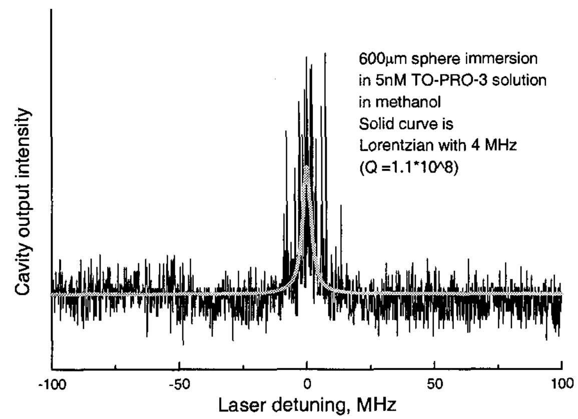
(Alyrzayev, Gorodetsky, Ilchenko, 1994, Unpublished)

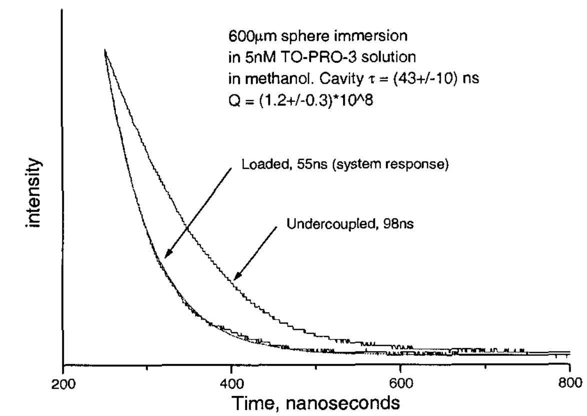
Immersion in pure solvent: background loss allows Q~10^9

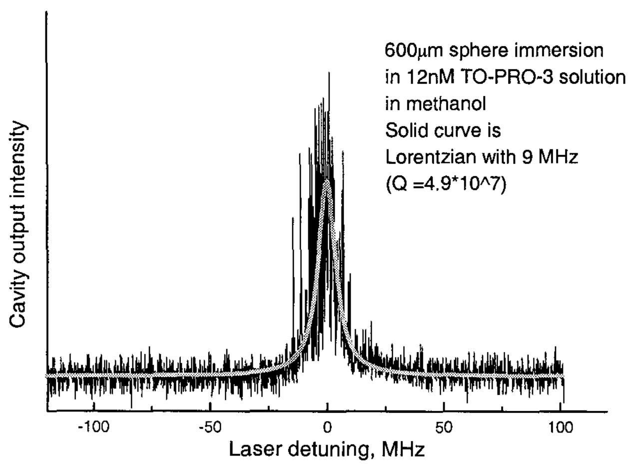


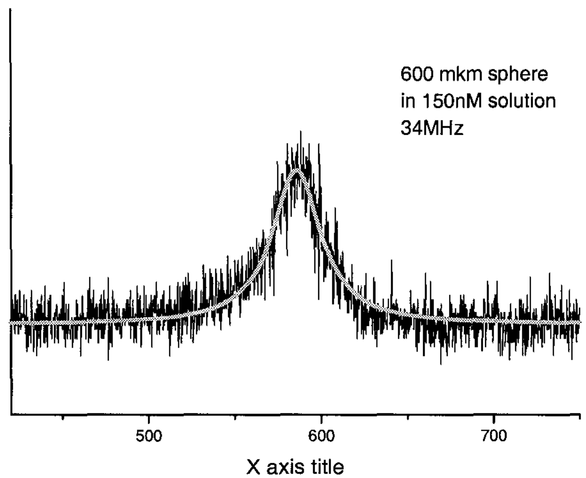
Demonstration: dissolving TO-PRO-3 fluorescent dye

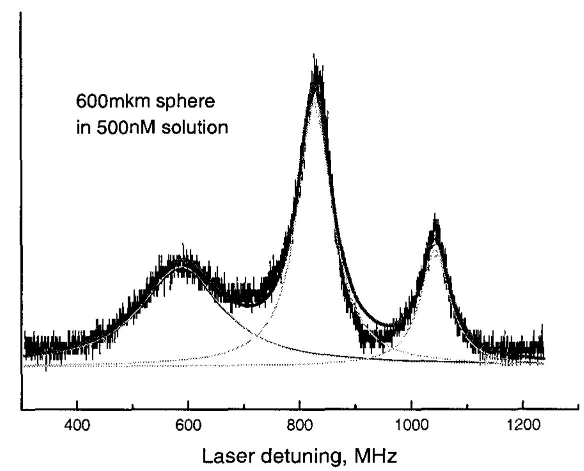


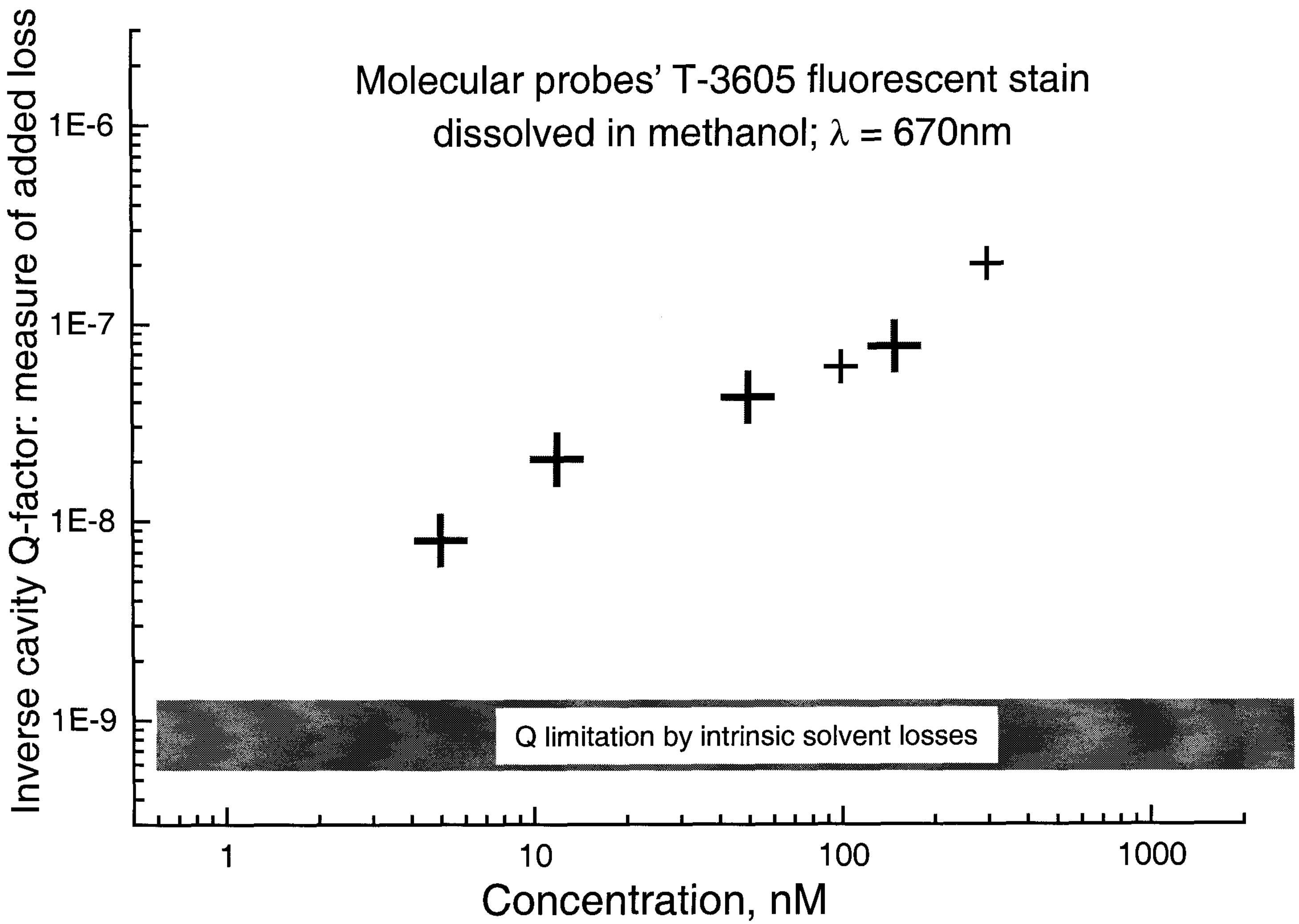











Molecular probes' T-3605 fluorescent stain
dissolved in methanol; λ = 670nm
Inverse cavity Q-factor: measure of added loss
1E-6
1E-7
1E-8
1E-9
Q limitation by intrinsic solvent losses
1
10
100
1000
Concentration, nM

CONCLUSION: WG microcavity as a sensor

- Immersed microsphere cavity is a novel micro multi-path cell for detection and, later, (cavity ringdown) spectroscopy of very dilute species

- Detectable concentrations of analytes, currently at nanoMole levels, can be reduced to sub-picoMole -- in a pure added-absorption method. Actual sampled volume is in the range of 10^{-9} cm^3 (“attoliter”):
  -- just thousands of molecules act

- Choice of solvents may not be limited to $n < n_{silica}$:
  immersed sphere can be inverted

CONCLUSION (General)

High-Q microcavities with whispering-gallery modes
reveal continued capabilities for research and applications